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BUREAU OF SOILS—BULLETIN No. 19.

MILTON WHITNEY, Chief of Bureau.

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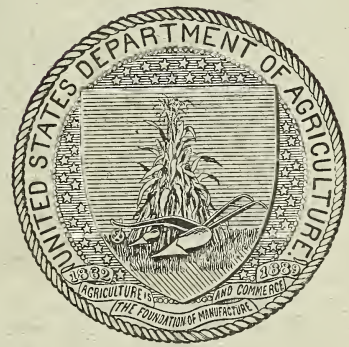
CAPILLARY STUDIES

AND

FILTRATION OF CLAY FROM SOIL SOLUTIONS.

BY

LYMAN J. BRIGGS AND MACY H. LAPHAM.



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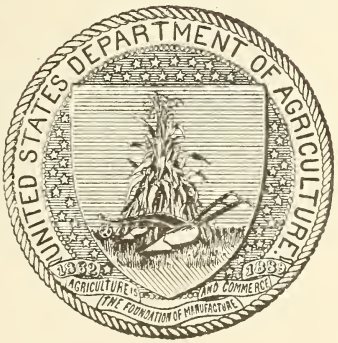

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1902.

LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Soils,
Washington, D. C., December 11, 1901.

Sir: I have the honor to transmit herewith the manuscript of technical papers by Lyman J. Briggs, Physicist of the Bureau, assisted by Macy H. Lapham, also of this Bureau, on the influence of dissolved salts on the capillary rise of soil waters, and other subjects. I recommend that these papers be published as Bulletin No. 19 of the Bureau of Soils.

Respectfully,

Milton Whitney,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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CAPILLARY STUDIES AND FILTRATION OF CLAY FROM SOIL SOLUTIONS.

INFLUENCE OF DISSOLVED SALTS ON THE CAPILLARY RISE OF SOIL WATERS.

By Lyman J. Briggs and Macy H. Lapham.

INTRODUCTION.

The so-called capillary "power" of a soil is generally measured in terms of the vertical height through which a soil can raise water by capillary action. This property varies greatly with different soils. In regions subject to prolonged droughts certain soils having a marked capillary action yield good returns under cultivation, while neighboring soils are practically barren. Professor Whitney[a] has noted a striking example of extensive capillary action in certain soils of southern California, which are able to mature summer crops without irrigation, while the total rainfall from May to September, inclusive, is less than 1 inch. In this region the water table is 20 feet or more below the surface. Means and Gardner[b] also mention an unusual capillary activity in the "gypsum loam" of the Pecos Valley, and numerous other instances might be cited.

When a soil contains a considerable amount of readily soluble material, extensive capillary action is apt to become a detriment rather than an advantage. The capillary movement of the moisture toward the surface results in the accumulation of the soluble substances in the stratum of soil normally occupied by the roots of the crop, and while the soluble salts as originally distributed through the soil may not be sufficiently concentrated to cause injury, the accumulation of the salts near the surface resulting from excessive evaporation frequently gives rise to an "alkali" soil. According to Means and Gardner, the cultivation of the "gypsum loam" above mentioned has been rendered very difficult on this account.

The deposition of salts at or near the surface of the soil is in general the direct result of an excessive evaporation; but it also represents indirectly a more or less extensive capillary action, since the surface

[a] Some interesting soil problems, Yearbook, U. S. Dept. Agr., 1897, p. 432.

[b] Soil survey of the Pecos Valley, New Mexico, Report 64, U. S. Dept. Agr., 1899, p. 68.

accumulation of salts is frequently much greater in quantity than could be obtained from the mass of soil near the surface. In some cases this is due to the arrival within the zone of capillary action of seepage waters containing a large percentage of soluble matter. Such conditions afford a basis for investigating the extent of capillary action only when the history of the seepage-water level is known, and will not therefore be further considered at present. In other cases, where the topography and other conditions are such as to preclude the possibility of the soil mass of an area having been polluted with soluble salts from other areas, the amount of soluble material at the surface as compared with that found a short distance below the surface serves to indicate the extent of capillary action, and may be made the basis of its computation.

The problem of the extent of capillary action is considered more fully in an accompanying paper. The object of the present investigation was to determine to what extent capillary action is influenced by the salts carried in solution.[a]

It has been shown in a previous paper[b] that the capillary movement of water in soils is dependent upon the curvature of the capillary water surfaces formed around the points of contact between the soil grains. The force exerted by these surfaces is equal to the product of their curvature and the surface tension of the water-air surface. The extent of capillary action, therefore, varies directly with the surface tension,[c] which in turn is dependent upon the dissolved salts in the soil waters, since the surface tension of an aqueous solution of a salt in general differs from that of the solvent. Dorsey,[d] working on solutions less than one-half normal, and Sentis,[e] on concentrated solutions, have shown that the surface tension is practically a linear function of the concentration. If we represent this relation for any given temperature by the expression

$$T_s = T_w + KC \tag{1}$$

where T_s is the surface tension in dynes per centimeter of the solution

[a] Very little work appears to have been done upon this phase of capillary action. Warington (Physical Properties of Soil, p. 105) states that "the results at present (1900) obtained are not sufficiently definite to justify any practical conclusions on the subject." Since Warington's book was published a paper has appeared by Krawkow, of St. Petersburg (Journ. für Landwirtshaft, **48**, 209 (1900); Abst. Chem. Centr., 1900, II, 1084). This paper deals with the influence of dissolved salts on the rate of capillary rise in a dry soil. Capillary columns only 40 cm. in length were used, so that nothing can be determined regarding the capillary limits, since the solution in every case reached the top of the column. Krawkow found that the solutions moved less rapidly than pure water, which could have been predicted with considerable assurance from the increased viscosity of the solutions.

[b] Mechanics of Soil Moisture. Briggs, Bul. 10, Division of Soils, U. S. Dept. Agr., 1897.

[c] For a fuller discussion of this point see "Mechanics of Soil Moisture," loc. cit.

[d] Physical Review, **5**, p. 228, 1897.

[e] Journ. de Phys. (3), **6**, p. 183, 1897.

of concentration, C, and T_w the surface tension of the solvent water, then K is a constant for any single solute, but varies with different salts. The concentration, C, is expressed in gram-molecules per liter.

From equation (1) it will be seen that K represents the difference in surface tension between a normal solution of a salt and its solvent. Since the surface tension of the solvent varies with temperature, K in general varies with temperature. Dorsey obtained the following values for K at 18° C.:

NaCl	$K = 1.53$
KCl	$K = 1.71$
$\frac{1}{2}$ (Na_2CO_3 + 10aq)	$K = 2.00$
$\frac{1}{2}$ (K_2CO_3 + 2aq)	$K = 1.77$

No reliable determinations seem to have been made for sodium sulphate, the other salt used in our investigations.

CERTAIN FACTORS MODIFYING CAPILLARY ACTION.

Before proceeding to the discussion and comparison of the experimental results obtained it will be advisable to consider somewhat more in detail certain factors which modify the movement of water in capillary spaces.

Resistance offered by a film to a shearing stress.—Suppose a drop of a liquid be applied to a dry, chemically clean surface, which it moistens. The liquid spreads over the surface until a condition of equilibrium is finally reached. Accepting for the present the conventional explanation of capillary movement as being the result of tensions in the bounding surfaces, the liquid is drawn over the surface owing to the existence of an air-solid surface tension, and this movement is opposed by the tensions of the air-liquid and liquid-solid surfaces. The magnitude of the three surface tensions is generally considered as sufficient to define completely the behavior of the drop, assuming gravity to exert no disturbing influence. As a result of our experimental investigations, however, we have been led to believe that in considering the forces opposing the movement of the liquid over the solid there must be taken into consideration also the resistance to a tangential shearing stress presented by the thin layer of liquid near its bounding edge. While no direct experimental evidence can as yet be given in support of this view, our experimental results show a marked diminution in the height of the capillary column in the case of concentrated solutions that can be satisfactorily accounted for on this assumption. This resistance of the film to a tangential shearing stress must not be confused with the viscosity of the solution, which has to deal with the liquid in mass, and refers to the rate of flow of the liquid when acted upon by an infinitesimal force. The resistance to a shearing stress appears only when the film has become so attenuated that it no longer behaves as a viscous liquid.

In the case of a more resistant liquid the peripheral layer must necessarily be somewhat thicker to offer the same resistance to further motion of the liquid, assuming the other forces to remain the same. Therefore for two liquids having the same surface tension the less resistant would attain the greater capillary height under identical conditions, since the film of liquid over the solid particles would be thinner and a greater distribution of the same weight of liquid would result. Since the surface tension of the two liquids is assumed to be the same, the weight of liquid supported in the two cases must be the same, assuming the resistance offered by the attenuated films to be the same when a condition of equilibrium is reached. However, it is probable that the soil tube containing the less resistant liquid would have a slightly greater weight of solution, since it is distributed over a greater amount of surface, and there is consequently a proportional increase in the amount of hygroscopic water which would not be included in the mass supported by surface tension.

Surface tension of solutions.—The surface tension of pure water, as determined by various observers, appeared to be about 73 dynes per centimeter at 18° C. From the formula given on page 6, together with Dorsey's values for K, we can easily compute the surface tensions of the sodium chloride and sodium carbonate solutions used, which are given in the following table:

TABLE I.—*Relative surface tension of solutions as compared with water.*

Substance.	Concentration.	Density.	$R = T_s \div T_w$.
	Per cent.		
Water	.....	1.00	1.00
N/2 NaCl	2.9	1.021	1.01
N/2 Na_2CO_3	2.6	1.03	1.014
N/2 Na_2SO_4	3.5	1.03	.....
20 per cent NaCl	20.00	1.15	1.072
20 per cent Na_2CO_3	20.00	1.23	1.104
20 per cent Na_2SO_4	20.00	1.19	.....
Saturated NaCl, 18° C	36.1	1.27	1.132
Saturated Na_2CO_3, 18° C	29.7	1.26	1.11
Saturated Na_2SO_4, 18° C	43.4	1.40	.....

The above results are calculated on the basis of pure water; that is, water which has been freed as completely as possible from all traces of grease or other substances that lower the surface tension. The water and the solutions used in these experiments can not be assumed to be in this state of purity as regards freedom from traces of oily substances, particularly after being in contact with the soil. To provide a basis for the comparison of our results we are therefore obliged to assume that the percentage of increase in the surface tension when a salt is added to water is independent, within certain limits, of the original surface tension of the water. Experiments by Lord Rayleigh

and others justify us in making this assumption with reference to our results.

Assuming for the moment that, with the exception of surface tension, all the properties of the several solutions employed are identical, it would follow that the capillary rise would be directly proportional to the surface tension. The relative capillary rise under such conditions as compared with pure water is shown in the last column of Table I.

It must, however, be borne in mind that these determinations have been made under conditions differing from those observed in this experiment in one important particular. In all surface-tension measurements the influence of the retaining solid surface is eliminated by first wetting it thoroughly with the liquid under investigation. Observing this precaution, it is immaterial what solid substance is employed, provided it is insoluble and is readily wetted by the liquid. In the case of our results, however, the influence of the solid surface enters directly, since it is the capillary rise of solutions in dry soils that is under investigation. The marked influence of the solid in such cases has been pointed out in an accompanying paper.[a] It is there shown that for the soil used in the present investigation the capillary rise in the dry soil is less than one-fourth the vertical height through which an upward movement of water will occur in the same soil in a moist state. Since, however, we are comparing the capillary rise of pure water and solutions, the influence of the solid wall does not enter, except in so far as the attraction of the solution for the solid wall differs from that of the solvent. It appears to be impossible to distinguish this factor experimentally from the accompanying influence of the contact angle between the liquid and solid surfaces.

Distribution of a liquid in a soil column through capillary action.—As we have already seen, when equilibrium is established the capillary forces are in part balanced by the weight of the suspended column of liquid. The capillary height attained is thus an inverse function of the density of the liquid. The relation is complicated by the fact that the solution is not uniformly distributed through the column, but decreases from the bottom toward the top. The exact nature of such a distribution has not been investigated, as far as we are aware.

A determination of the distribution of moisture in saturated soil columns after long standing has, however, recently been made by King.[b] In one case the tubes were drained and in the other case subjected to surface evaporation. While these conditions are by no means identical with the capillary rise of water in dry soils, they serve to give an idea of the distribution of water in a soil column after equilibrium has been reached. King's results show in a general way a linear

[a] Capillary Movement of Water in Dry and Moist Soils. Briggs and Lapham, this bulletin, p. 19.

[b] Sixteenth Annual Report Wis. Expt. Sta., 1889, p. 24.

gradient, although many irregularities occur, probably due to lack of uniformity in the soil column.

In the case of capillary columns of approximately the same height the distribution of the solutions can without serious error be assumed the same, and consequently neglected; but in the case of columns of different heights we are not justified a priori in making this statement.

Owing to the lack of specific data we shall assume, as a basis for the comparison of our results, that the distribution is the same and that the gradient is linear; i. e., the amount of solution in the soil column diminishes uniformly from bottom to top. This assumption is supported by King's results. The relative weights of the two capillary columns would on this basis be proportional to the heights of the columns multiplied by the density of the solutions.

Relation between capillary height, surface tension, and density.— From the relation given above we can obtain a provisional expression for the relation between the capillary height of a solution and of pure water, as follows:

$$\frac{D_s H_s}{T_s} = \frac{D_w H_w}{T_w} \tag{2}$$

in which H_s and H_w are the capillary heights, T_s and T_w the surface tensions, and D_s and D_w the densities of the solution and distilled water, respectively.

Solving equation (2) for H_s and putting $D_w = 1$, we have

$$H_s = \frac{H_w\, T_s}{T_w\, D_s} \tag{3}$$

But $\frac{T_s}{T_w}$ is the ratio of surface tension as given in Table I.

Putting $\frac{T_s}{T_w} = R$ and substituting in (3),

$$H_s = \frac{H_w\, R}{D_s} \tag{4}$$

It will be noted that this expression is identical with that giving the relation between the heights of the two liquids in capillary tubes of the same diameter.

PLAN OF EXPERIMENTS.

Solutions.—In making an experimental study of the effect of dissolved salts on the capillary rise of soil moisture, it was decided to use only those salts which are found in excess in "alkali" soils, since it is chiefly in connection with these salts that investigation has a practical bearing. Accordingly, sodium chloride, sodium carbonate, and sodium sulphate were selected, and two solutions of each salt were used. One series was approximately one-half normal in concentra-

tion, while in the other series the solutions were in one case saturated and in contact with the solid salt, while in the other case 20 per cent solutions were employed. Chemically pure salts were used.

In making up the solutions distilled water from a block-tin still was used. The water may therefore be considered to be as free from grease as can be obtained by this method. As a further precaution check experiments were made with water alone, with which the results obtained with the solutions were always compared, so that the influence of exceedingly slight amounts of grease will not appear.

Soil.—The soil used was from James Island, South Carolina. This type was selected on account of its texture, which enables the capillary water to ascend rapidly and equilibrium to be attained within a reasonable time. Furthermore, this type of soil was used in a previous series of experiments,[a] which are directly related to the present subject.

A mechanical analysis of this soil is given below.

Mechanical analysis of soil from James Island, South Carolina.

Diameter in millimeters.	Conventional name.	Per cent.
2 to 1	Fine gravel	0.00
1 to .5	Coarse sand	.37
.5 to .25	Medium sand	6.01
.25 to .1	Fine sand	79.15
.1 to .05	Very fine sand	2.50
.05 to .01	Silt	.55
.01 to .005	Fine silt	4.23
.005 to 0	Clay	4.60
Loss at 110° C		.83
Loss on ignition		1.85

The soil ordinarily contains quite an appreciable amount of soluble salts, principally sodium chloride. It was therefore repeatedly washed by decantation with distilled water until practically no more salts went into solution. This was quickly and conveniently determined by measuring the electrical conductivity of the decanted water.

Apparatus.—Glass tubes 2.5 cm. in internal diameter were used for holding the soil while determining the capillary rise of the different solutions. The tubes were supported vertically in a frame, each tube being kept in position by means of strong elastic bands pressing it into a V-shaped incision in the frame. A cork ring was fitted into the lower end of each tube, to the outer face of which a disk of fine brass-wire gauze was cemented with marine glue. The construction is shown in longitudinal section in fig. 1. This form of construction makes a very rigid base for the soil column and reduces the liability of the column becoming separated through a movement of the base.

[a] Salts as Influencing the Rate of Evaporation of Water from Soils. Briggs, Report 64, U. S. Dept. Agr., 1900.

A wisp of glass wool was placed over the gauze to prevent the soil from sifting through.

The soil was then introduced into the tube in an air-dry condition. Stratification while filling was successfully avoided by keeping the tube at an angle of about 30° with the horizontal and constantly stirring the soil in the tube with a heavy wire bent into an open helix at one end. Frequent jarring with the tube in a vertical position is advisable to secure as compact a condition as possible.

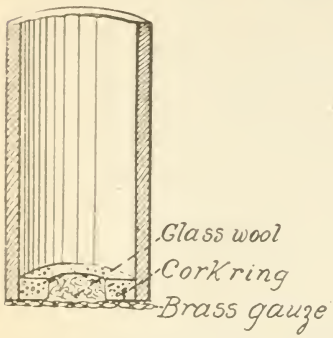

FIG. 1.—Vertical section through base of soil tube, showing construction.

The lower end of each tube rested upon a cork ring in the bottom of the solution jar. This served to fix definitely the position of the tube with reference to the surface of the solution. One side of the ring was cut away to allow the solution to have free access to the tube.

The surface of each solution at the beginning of the experiment was adjusted to a given height above the immersed end of the tube, and the level of the liquid was afterwards maintained constantly at this height by the use of an automatic device controlling an auxiliary supply. A modified Mariotte apparatus, of the form shown in fig. 2, was first used for this purpose, the level of the solution being adjusted by raising or lowering the tube *a*. Evaporation of the liquid was reduced to a minimum by the use of a well-fitted cover.

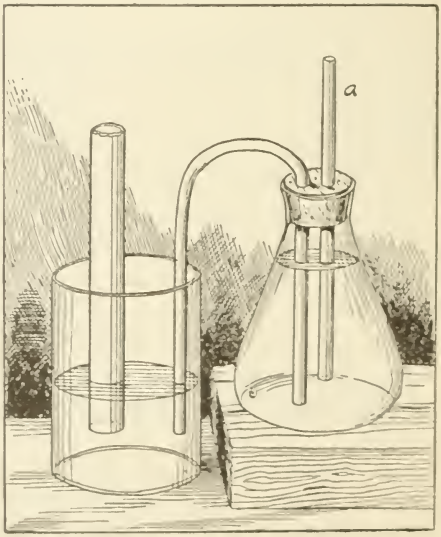

FIG. 2.—Mariotte apparatus for maintaining solution in reservoir at a given height.

The Mariotte apparatus failed to work in some cases in the positive manner desired, and later it was discarded for the simple apparatus shown in fig. 3, which was brought to our attention by Mr. A. H. Seidell. As will be seen from the figure, the apparatus consists of an inverted stoppered flask containing the solution and provided with a delivery tube reaching below the surface of the solution in the open jar. The essential feature of the apparatus is a small hole in the side of the delivery tube at the surface of the liquid, which, when partially uncovered by the removal of the

solution, permits a bubble of air to ascend the tube, thus allowing a small amount of the solution to escape from the flask into the jar. The delivery tube should be large enough to enable the air bubble to move readily up the tube. The hole in the side should be about 3 mm. in diameter. This simple arrangement maintains a constant level in a most satisfactory manner. In a series of ten observations the mean variation in the level of the liquid was found to be less than 0.7 mm.

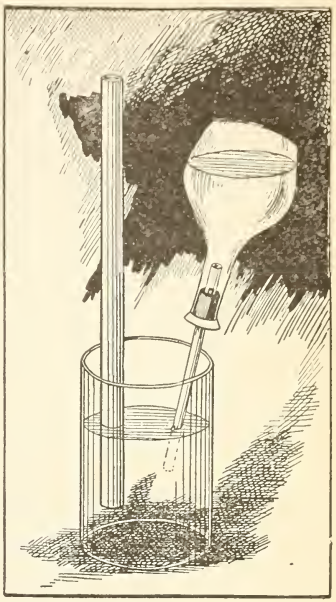

FIG. 3.—Apparatus for automatically maintaining solution in reservoir at any desired height.

CAPILLARY RISE OF WATER AND SALT SOLUTIONS IN SEA ISLAND SOIL.

A part of the data obtained regarding the capillary rise of water and salt solutions in Sea Island soil is given in the following table. The first column gives the time in hours during which capillary action took place. The second column gives the height attained by distilled water through capillary action during the time indicated in the first column. The remaining columns give the corresponding heights of the several solutions.

TABLE II.—*Capillary rise of salt solutions in dry Sea Island soil.*

Time.	Water.	N/2 solutions.			Saturated solutions.		
		NaCl.	Na_2CO_3.	Na_2SO_4.	NaCl.	Na_2CO_3.	Na_2SO_4.
Hours.	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*	*cm.*
0	0	0	0	0	0	0	0
½	21.2	21.2	21.2	20	13.7	14.4	13.1
1	26.9	23.1	22.5	22.5	13.7	15	13.1
1½	28.4	24.4	23.7	23.7	14.4	16.9	13.1
2	28.4	25.6	24.4	25	14.4	17.5	13.1
3	30	27.5	25.6	26.9	15	15	13.7
4	30	28.1	26.2	27.5	15	16.9	13.7
5	30	28.7	26.9	28.1	15.6	18.7	13.7
6	30.6	28.4	27.5	28.7	16.9	22.5	15.6
23	32.5	31.9	31.2	31.2	18.1	25.6	16.2
30	32.5	32.5	31.9	31.2	18.7	26.2	17.5
47	33.1	32.8	33.1	31.9	19.1	26.9	17.8
72	33.6	33.4	33.4	32.8	19.1	27.2	18.1
120	34.7	34.4	35.9	34.1	19.7	27.8	19.1
168	35.3	35	36.9	34.4	20.3	28.1	19.7
216	36.2	35.6	38.1	35.3	20.6	28.7	20
288	37.1	36.6	39.4	36.6	20.9	29.4	20.6
336	37.5	36.9	40	36.9	21.2	30	21.2

It will be noted that the saturated solutions in Table II do not reach the height attained by distilled water or by solutions of lesser concentration. This result is directly opposed to the conclusions reached in the first part of this paper, namely, that surface tension, and consequently capillary action, increases with the concentration. As will be shown later, such action is opposed by the greater density of the solution, though not to an extent sufficient to account for the observed discrepancy. It was thought that this discrepancy might be due to the crystallizing out of the salt from the saturated solutions within the tubes, thus preventing further capillary rise of the solution. We, accordingly, decided to repeat the experiments with 20 per cent solutions. Within the range of temperature met during the course of the experiments no separation of the solid salts would take place at this concentration. Any error due to the crystallization of salts in the tubes would consequently be avoided.

The results obtained with 20 per cent solutions are given in the following table:

TABLE III.—*Capillary rise of concentrated salt solutions in dry Sea Island soil.*

Time.	20 per cent solutions.			Time.	20 per cent solutions.		
	NaCl.	Na_2CO_3.	Na_2SO_4.		NaCl.	Na_2CO_3.	Na_2SO_4.
Hours.	*cm.*	*cm.*	*cm.*	*Hours.*	*cm.*	*cm.*	*cm.*
0	0	0	0	168	25	30.3	24.1
½	16.6	13.7	11.6	264	25.6	31.6	25
1	18.4	17.8	13.4	408	26.9	33.1	25.9
1½	19.1	19.7	14.7	552	27.5	34.1	26.9
2	19.1	20.9	14.7	744	28.1	35.6	27.8
4	20	23.4	17 2	912	28.7	36.2	29.1
6	20.6	24.7	18 4	1,080	29.2	36.9	29.1
24	21.9	26.6	21.2	1,248	29.6	37.5	30.6
48	23.1	27.5	22.2	1,416	30.3	37.5	30.9
96	24.1	29.1	23.1	1,608	30.5	38.7	31.6

DISCUSSION OF RESULTS.

We proceed now with the application of the principles considered above to our experimental results.

Half-normal solutions.—From the data given in Table I it will be seen that the surface tension of a one-half normal sodium chloride solution is about 1 per cent greater than that of water; that is, $R = 1.01$. The density of this solution is stated by Reyher[a] to be 1.0208. From equation (4) we calculate the height of the capillary column of this solution to be 37.1 cm. The observed height, as will be seen from Table II, was 36.9 cm., an agreement within the limit of experimental error. In making a comparison between observed and calculated results the final observations only are to be considered, since it is only

[a] Ztschr. fur Phys. Chem., 2, 749.

when equilibrium is practically established that a comparison on the above basis can be made.

No determination of K' for sodium sulphate is available. It will be noted, however, that K' does not vary greatly for the salts given in Table I, so that we may assume without serious error the constant for sodium sulphate and sodium chloride to be the same. The computed surface tension would then be the same as before, and the experimental results show the two salts to have the same capillary rise at this concentration.

Saturated solutions.—Turning now to the saturated solutions, we find the capillary height attained by saturated sodium chloride, as calculated from equation (4), to be 33.4 cm. The observed capillary rise is, however, only 21.2 cm.

This great discrepancy was, at the time of making the experiments, supposed to be due to the separation of the solid salt in the tubes, preventing further capillary action.

Twenty per cent solutions.—On account of the supposed separation of the solid phase, the experiments were repeated with 20 per cent solutions, the results being given in Table III.

Computing, as before, the capillary rise from the data given in Table I, we find the calculated capillary height of the 20 per cent sodium chloride solution to be 35 cm., while the observed height is 30. 5 cm.

CONCLUSIONS REGARDING SODIUM CHLORIDE AND SODIUM SULPHATE.

That the sodium chloride solution had reached a condition of capillary equilibrium at the time the final observation in Table II was made seems beyond reasonable doubt, the total capillary rise during the last two weeks of the experiment being only 2 mm. Neither can the separation of the solid salt in this case be seriously entertained as a possible explanation of the observed results. Further, the similar behavior of the sodium sulphate solutions, together with the saturated solutions, serves to substantiate the reliability of the results. In explanation, therefore, of the marked discrepancy between the observed and calculated results for concentrated solutions, while agreeing for dilute solutions, we suggest that it is due, in part at least, to the resistance offered by the concentrated films to a tangential shearing stress, which serves to prevent the attenuation of the films taking place to the extent occurring in more dilute solutions, and thus changes the contact angle. The diminution of the capillary height due to this cause may not take place to the extent indicated by our calculations, since the distribution of the liquid in the capillary column is not sufficiently well known; but the existence of some modifying agency of this kind, in connection with capillary action in concentrated solutions, seems to have been established. It should be noted that this effect would be produced by an increase in the tension of the liquid-solid surface with the concentrated solutions.

The marked diminution in the capillary rise of the saturated solutions

can, in the light of the evidence just discussed, reasonably be ascribed to the same cause, or at least in greater part. In the case of the more dilute solutions this factor does not appear to exercise an appreciable influence, and consequently it may be neglected in considering the capillary movement of soil waters, except in the case of concentrated solutions. It is desirable that other salts and other soils be investigated in order to study more thoroughly the influence of this heretofore unrecognized factor in the capillary phenomena of soils.

SODIUM CARBONATE.

The discussion of the data for sodium carbonate has purposely been deferred in order that a separate treatment might be given. Solutions of this salt show a marked increase in capillary action as compared with the sodium salts of the stronger acids. In Table II it will be noted that the half-normal (N/2) sodium carbonate solution attains a capillary height of 40 cm., as compared with 37.5 cm. for water and 36.9 cm. for the solutions of the other sodium salts of equal concentration. In the case of the saturated solutions the difference is much more marked, the sodium carbonate solutions rising 30 cm. and the other solutions only 21.2 cm. Finally, the 20 per cent sodium carbonate solutions attained a height of 38.7 cm., as compared with 30.5 cm. for sodium chloride and 31.6 for sodium sulphate. It will thus be noted that dilute sodium-carbonate solutions attain a greater capillary height than distilled water, and in every case the sodium carbonate is more active than the other sodium salts.

Characteristics of capillary column with sodium carbonate solutions.— During the latter part of the experimental period some very interesting and instructive changes occurred in the extreme upper portions of the capillary column. During the earlier stages of the experiments the plane of contact between the moist and dry soil above was very distinct for all the solutions. This continued to the end in the case of the sodium chloride and sodium sulphate solutions for all concentrations; but with sodium carbonate solutions the moisture in the upper part of the capillary column diminished so gradually that it was almost impossible to locate accurately the actual boundary between dry and moist soil. The light gray color of the dry soil in the tube shaded uniformly into the darker color of the moist soil below. This was especially true in the case of the more dilute sodium carbonate solutions. With the more concentrated solutions the shading was somewhat more abrupt and the boundary better defined.

TENTATIVE EXPLANATION OF SUPERIOR CAPILLARY ACTIVITY OF SODIUM CARBONATE.

We have now to consider another factor bearing on the explanation of the unique capillary activity of sodium carbonate. The surface of

all solid bodies that have not been specially cleansed become in time more or less contaminated from various sources with grease in some form, or with substances having the same action as grease on surface tension. This is particularly noticeable with respect to glass surfaces, water refusing to spread uniformly over a glass surface unless rigid precautions have previously been taken to remove the invisible film of residual grease. The same effect is also very noticeable in many soils, which show the greatest reluctance with regard to absorbing water after having been thoroughly dried.

An explanation of the increased capillary activity of sodium carbonate in the light of the above observations appears possible. Sodium carbonate in aqueous solution hydrolyzes to some extent, forming sodium hydroxide and sodium hydrogen carbonate. The sodium hydroxide reacts with the grease, forming a water-soluble sodium salt or soap. The oily substances are in this way completely removed from the surfaces of the soil grains, which become clean so far as grease is concerned and are readily "wetted" by water. This accounts for the extreme attenuation of the films in the upper end of the capillary columns with sodium carbonate solutions.

Sodium chloride and sodium sulphate do not hydrolyze to any appreciable extent, so that no saponification of the grease takes place with these solutions. Capillary rise is thus to some extent diminished. The presence of the grease serves to diminish the molecular attraction between the solution and the surfaces of the soil grains, and the diminished capillary action results.

Any salt capable of an alkaline hydrolysis—that is, one consisting of a comparatively strong base and a weak acid—is capable of saponifying the greasy substances, and should give the attenuated films formed with the sodium carbonate solutions. Thus this effect might be expected from the carbonates, borates, and phosphates of the alkaline metals, and to some extent, perhaps, with calcium and magnesium, although the slight solubility of the calcium and magnesium salts in some instances would prevent a marked effect. It is proposed to investigate this point more in detail.

POSSIBLE INFLUENCE OF ABSORBED GASES ON CAPILLARY PHENOMENA.

It will be shown in another paper that there is a relatively large amount of carbon dioxide absorbed or condensed on the surface of the soil grains. The interesting query suggests itself, Does the absorbed carbon dioxide interfere with capillary action? Several interesting bits of evidence lend support to an affirmative answer to this question. For example, freshly drawn capillary tubes give higher readings in surface-tension experiments than old tubes of the same diameter. Further, in the experiments with sodium carbonate described above,

the carbon dioxide on the surface of the grains is removed by reacting with the sodium carbonate in accordance with the following expression:

$$Na_2CO_3+CO_2+H_2O=2NaHCO_3.$$

It must be admitted, however, that both conditions might be explained on the supposition of a thin film of grease. The latter seems the more rational in view of the fact that dissolved carbon dioxide does not lower the surface tension of the liquid.

SUMMARY.

From the results given in the paper the following conclusions may be drawn:

(1) Dissolved salts in general do not increase the capillary rise of soil waters.

(2) Neutral salts in dilute solution have practically no influence on the extent of capillary action.

(3) Concentrated or saturated solutions of all salts materially diminish capillary activity.

(4) This effect appears to be due—

(*a*) To the increased density of the solution, which more than offsets the increased surface tension, and—

(*b*) To the resistance of a film to a tangential shearing stress, which retards capillary action and offers in addition a permanent resistance to the movement of the solution through thin films, thus increasing the angle of contact, or—

(*c*) To an increase in the tension of the liquid-solid surface, as the concentration is increased.

(5) Sodium carbonate differs from neutral salts, the capillary rise being considerably greater than for neutral solutions of equal concentration.

(6) This may be due in part to the saponification of traces of grease on the surface of the soil grains through the hydrolysis of the sodium carbonate, thus furnishing clean surfaces for capillary action.

(7) The same effect should consequently be observed with all salts which undergo an alkaline hydrolysis, viz, potassium and sodium carbonates, borates, phosphates, etc.

(8) This action is characterized in the soil tubes by indistinctness of the upper boundary of the capillary column.

THE CAPILLARY MOVEMENT OF WATER IN DRY AND MOIST SOILS.

By Lyman J. Briggs and Macy H. Lapham.

INTRODUCTION.

The capillary activity of a soil in its relation to water is generally conceded to be one of its most important attributes, and the ability of certain soils to support plant life for relatively long periods without rain or irrigation is usually explained on this basis. Certain soils in southern California possess this characteristic to a marked degree,[a] being able to mature sugar beets and other summer crops without a drop of rain from the time the crop is planted until it is harvested, and with no irrigation. Other examples are cited elsewhere.[b]

Comparatively nothing, however, is really known about capillary action in these soils under field conditions; and there is no experimental proof to show that the vigorous plant development obtained may not really be due to an extensive root system made possible by a favorable soil structure. It was with the object of determining the extent of capillary action under such conditions that the investigation was undertaken, the preliminary results of which are given in this paper.

The rapidity of the distribution of moisture and the extent of its movement constitute the two most important factors in capillary action. The conventional method of investigating the numerical value of these factors consists in determining the rate of ascent and the vertical height through which water will rise by capillary action in a dry soil. By "dry," as used in this sense, is meant an air-dried soil, which is consequently subject to the variation in hygroscopic moisture resulting from the usual changes in atmospheric temperature and humidity. So far as we are aware, the influence of hygroscopic moisture on capillary action has never been investigated.

The results of investigations on the capillary rise of water in dry soils, where they have been applied at all, have usually been taken to

[a] Some Interesting Soil Problems. By Milton Whitney. Yearbook, U. S. Dept. Agr., 1897, p. 432.

[b] This bulletin, p. 5.

represent the limit of capillary action under field conditions. It is the object of the present paper, first, to emphasize the fact that such observations with dry soils do not represent the range of capillary action in the field, and, second, to consider the magnitude and ratio of the distances through which capillary action will take place in a soil when dry and when in a moist state.

Numerous determinations of the capillary rise of water in dry soils have been made by various observers in the United States, those of Loughridge[a] on California soils being among the best. Loughridge finds for the soils he investigated, which included adobe and silty soils, that the capillary rise in no case exceeded 50 inches, even at the expiration of two hundred days.

Professor King,[b] in 1889, investigated the capillary movement of water in a moist sand resembling quicksand, which underlies the Wisconsin experimental farm, and found a very appreciable capillary movement of water upward through a vertical column of soil 4 feet in height—0.9 pound per square foot of surface exposed to evaporation per day. The capillary rise in the dry soil was not determined. From our own observations, however, it seems safe to assume that this distance would not exceed 2 feet.

In a recent paper Professor King gives the results of another set of experiments with moist soils, which he compares with Loughridge's results. The results obtained and the methods used will be discussed later.

OUTLINE OF INVESTIGATION.

It is evident from the preceding discussion that, if the great number of capillary experiments with dry soils which have been made are to be used in interpreting the behavior of soils under field conditions, it is absolutely necessary to know the ratio between the capillary rise of water in a soil in a dry and in a moist state. Further, in order to distinguish in the field between the effect of extensive root systems and capillary action, it is necessary to know the maximum limit of capillary action in a given moist soil, together with the rate at which water can be supplied under given conditions.

The problem as outlined entails a great amount of experimental work with different soil types before general conclusions can be reached. It may be possible that a constant ratio exists between the limits of capillary action in a soil when dry and when in a moist state; or if such a simple ratio can not be obtained a generalization may still be possible by introducing a term depending on the texture of the soil. Any relation of this kind would be of the greatest importance, not only for its intrinsic interest, but because the capillary rise in a

[a] California Station Report, 1892–93, p. 91.

[b] Sixth Report, Wis. Expt. Sta., 1889, p. 203.

soil in a dry state is much easier to determine than the upper limit of capillary movement in a moist soil, by methods at present available.

It is hoped that other workers in this field may find an opportunity to determine these constants for the type soils of the localities in which they are most interested. Such results would be of immediate interest, in connection with the other physical properties of the soil to which they apply, and in addition would be of great value in establishing the general relation before mentioned.

PLAN OF EXPERIMENTS.

In carrying out the investigation, as outlined above, two sets of experiments are necessary. First, the maximum capillary rise in the dry soil must be determined. The rate at which the water rises may also be determined, if desired, but this has little practical value as applied to field conditions. Second, the maximum height through which capillary action will take place in the moist soil must be found, and the rate at which water can be supplied at the surface by capillary action through lesser distances must be measured.

The method of procedure with the dry soil is familiar to all and needs no discussion here. A description of a convenient apparatus for this purpose, together with certain precautions to be observed, will be found in an accompanying paper.[a]

In determining the maximum height of capillary action in a moist soil we have adopted the following as defining the limit of capillary action. The limit of capillary action in a vertical column of moist soil is attained when the column is no longer able to supply to its upper surface, when exposed to evaporation, a finite, continuous, and approximately uniform supply of water obtained through capillary action from a reservoir at the base of the column. It will be evident, on consideration, that the supply must be continuous and approximately uniform in order to eliminate the case of the capillary movement of water in the upper portion of the column alone.

DESCRIPTION OF APPARATUS.

Two tubes of glass or copper 1 inch in diameter are provided with perforated bases and then carefully filled with the soil under investigation, following the directions given elsewhere.[b] The tubes are then saturated with water by immersing the bases of the tubes in a vessel of water and exhausting the tubes from the top. This procedure effectually avoids the trapping of air between two portions of the moist column. After saturation the tubes are protected from evaporation at the top and allowed to drain until equilibrium is attained. One tube is then sealed hermetically at the base and its upper surface

[a] This bulletin, p. 11.

[b] See paper on Influence of Dissolved Salts on Capillary Rise of Soil Waters, loc. cit.

exposed to evaporation. The other tube is sealed into a small water reservoir, as shown in fig. 4.

The space between the tube and the neck of the reservoir is filled with cotton, over which hot sealing wax is flowed and allowed to harden. This effectually prevents loss of water by direct evaporation from the reservoir. It is, however, necessary to maintain the interior of the reservoir at atmospheric pressure; otherwise the difference in pressure would modify the distribution of the water. Accordingly a capillary tube of very small bore is inserted through the reservoir neck, as shown in the figure, to equalize pressures. The evaporation through such a capillary opening may be safely considered negligible.

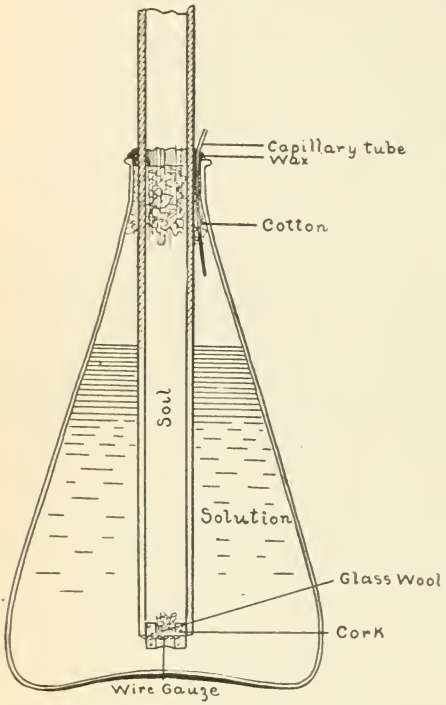

FIG. 4.—Water reservoir and soil tube used in determining the capillary limit in moist soils.

The two tubes are then exposed to evaporation under similar conditions. The evaporation from the tube with the sealed base may reasonably be expected to decrease gradually as the capillary water in the tube diminishes. If the column of soil in each tube is so long that the capillary water in the lower end of the tube is not affected by the evaporation at the surface, then the two tubes will behave alike, the amount of water evaporated per day gradually decreasing and finally ceasing. If, however, the adjustment of the capillary water in the soil column, resulting from surface evaporation, extends to the lower end of the tubes, the water thus removed will be replenished in the case of the tube provided with the reservoir, while with the sealed tube no such replenishment is possible. In the case of the reservoir tube, therefore, we get, after a certain time, a uniform rate of evaporation, provided the length of the soil column does not exceed the limit of capillary activity as defined above. With the sealed tube, on the other hand, we get only a gradually decreasing rate of evaporation, due to the removal of the capillary water.

The problem is, therefore, to determine the limiting height of a soil column capable of furnishing a finite and continuous quantity of water at its upper surface at approximately a uniform rate, replacing that lost through evaporation. The subject may be investigated from

either side; that is, we may first choose a soil column presumably greater than the one satisfying the conditions, so that the sealed tube and the reservoir tube should behave precisely the same, and we may then cut off a certain amount from the upper end of each tube, again test their behavior, and continue the process until a constant rate of evaporation is obtained from the reservoir tube.

The second method consists in increasing the length of the soil column by steps, either by employing a tube capable of being built up section by section or by simultaneously using a series of tubes of different lengths. We have not used sectional tubes and consequently can say nothing regarding the practicability of this plan. The simultaneous use of a number of tubes of different lengths would undoubtedly yield results quicker than the other methods, but would involve more work. In our experiments we have used mainly the first method described.

In each of the two methods described the loss due to evaporation is determined by weighing the whole system. This necessitates, as we have seen, the employment of an additional tube without a reservoir, in order to determine whether the observed loss is not all taking place from tube alone. A simpler method, involving the use of only one tube, consists in employing a detachable reservoir, which can be removed from the tube and the loss determined directly by weighing. This method has the advantage of avoiding any error arising from the comparison with a second tube. It can also be used with long tubes where the weighing of the whole system is impracticable. It is subject to slight errors, owing to the dependence of the water content of the soil column upon temperature and pressure. Care must be taken in using this method to avoid loss by evaporation from either the reservoir or the base of the soil tube during the weighing. The latter may be satisfactorily protected during this process by substituting an empty reservoir for the one removed. Should any dripping take place from the end of the tube, the second reservoir may be weighed and the necessary correction applied.

Wide-mouthed Erlenmeyer flasks make excellent reservoirs. A convenient way of fastening them to the soil tubes is to use one or more folds of the large thin-walled pure rubber tubing used in the Gooch crucible filter cups.

We have also found that quite satisfactory results may be obtained without making weighings. To this end a cylindrical glass reservoir is chosen, having an internal diameter slightly greater than the external diameter of the tube. If the amount of water in the reservoir is adjusted so that the meniscus is formed between the walls of the reservoir and the tube, any subsequent change in the volume of water in the reservoir will of course produce a change in the position of the meniscus. In this way qualitative and even roughly quantitative results may be obtained.

CAPILLARY RISE OF WATER IN DRY SEA ISLAND SOIL.

The capillary rise of water in air-dried Sea Island soil, as determined from duplicate experiments, is given in the following table:

TABLE I.—*Distilled water.*

Time in days.	Height of moisture.		Time in days.	Height of moisture.	
	No. 1.	No. 2.		No. 1.	No. 2.
	cm.	*cm.*		*cm.*	*cm.*
1	29.8	33	8	33.6	36.5
2	31.1	33.7	9	34	36.8
3	31.1	34.3	10	34.3	37.5
5	31.4	35.2	12	35.6	37.8
6	33	35.6	13	35.6	38.1
7	33	35.9	14	36.2	38.1

CAPILLARY RISE OF WATER IN MOIST SEA ISLAND SOIL.

Our first experiments on the capillary movement of water in moist Sea Island soil were made with a column 85 cm. in height. It will be seen that the height of this column is more than twice the capillary height attained in the dry soil. The tube was provided with a reservoir, as described above, and the loss due to evaporation was determined by weighing.

The following table gives the results obtained with the soil column:

TABLE II.—*Sea Island soil (column 85 cm. high).*

Time in days.	Weight.	Total amount evaporated.	Time in days.	Weight.	Total amount evaporated
	Grams.	*Grams.*		*Grams.*	*Grams.*
0	1,113.6	0	24	1,011.4	101.8
1	1,111	2.6	27	1,001.3	111.9
2	1,104.7	8.9	30	991.3	121.9
4	1,091.9	21.3	32	985.2	128
6	1,082	31.2	35	976.4	136.8
8	1,070.2	43	38	969.4	143.8
10	1,061.2	52	42	960.7	152.5
13	1,051.6	61.6	45	954.7	158.5
16	1,040.9	72.3	52	940	173.2
18	1,034.4	78.8	55	933.5	179.7
21	1,025.6	87.6			

These figures show very conclusively the marked capillary movement through a soil column of this height. In fact, the water in the reservoir was entirely removed in this way, a total amount of about 180 grams being evaporated in fifty-five days. The surface cross section of the tube was about 0.7 square inch, or 4.3 sq. cm. This corresponds to a mean value of 4.7 grams per square inch, or 1.09 grams per square centimeter, per day. This was under ordinary

conditions in a laboratory, the tube being kept in a well-ventilated hood. No attempt was made to keep the temperature or relative humidity constant, which accounts for irregularities from day to day. On the whole, however, the results show a continuous and approximately uniform rate of evaporation.

The next experiments were with columns of Sea Island soil, 180 cm. high. The results obtained are given in Table III.

TABLE III.—*Sea Island soil (columns 180 cm. high).*

Time in days.	Sealed tube.		Reservoir tube.	
	Weight.	Total amount evaporated.	Weight.	Total amount evaporated.
	Grams.	*Grams.*	*Grams.*	*Grams.*
0	1,523.5	0	1,987.5	0
1	1,520	3.5	1,984.8	2.7
2	1,518.5	5	1,983.9	3.6
4	1,516	7.5	1,981	6.5
6	1,513.5	10	1,980	7.5
10	1,512	11.5	1,979	8.5
13	1,510	13.5	1,977	10.5
17	1,508.6	14.9	1,975	12.5
24	1,506.2	17.3	1,972.5	15
31	1,505	18.5	1,971.2	16.3
36	1,504	19.5	1,970.2	17.3
41	1,502.8	20.7	1,968.2	19.3
46	1,502	21.5	1,966.2	21.3
50	1,501.2	22.3	1,965.1	22.4

The results in Table III show that the evaporation from the reservoir tube was no greater than from the sealed tube. It was evident, therefore, that the capillary limit had been exceeded and that Sea Island soil was not capable of maintaining a capillary movement through a vertical column 180 cm. The tubes were accordingly shortened 15 cm. and the experiment continued. The results are given in Table IV.

TABLE IV.—*Sea Island soil (columns 165 cm. high).*

Time in days.	Sealed tube.		Reservoir tube.	
	Weight.	Total amount evaporated.	Weight.	Total amount evaporated.
	Grams.	*Grams.*	*Grams.*	*Grams.*
0	1,561	0	1,978.5	0
3	1,560.2	.8	1,977.2	1.3
17	1,557	4	1,966.5	12
28	1,554.3	6.7	1,958.5	20
42	1,551.6	9.4	1,950.2	28.3

Table IV shows conclusively that a capillary movement has taken place through a column of Sea Island soil 165 cm. in height. This is

shown both by the greater evaporation from the reservoir tube and by the very noticeable diminution in the amount of water in the reservoir. The reservoir tube evaporated 28.3 grams of water in forty-two days, an average of 0.96 gram per square inch or 0.15 gram per square centimeter per day. The tubes were, however, close to a wall and poorly ventilated. The rate of evaporation for the 85 cm. tube was 1.09 grams per square centimeter per day (p. 24). It would be of interest to determine the rates for intermediate columns, and we expect to attempt this later.

DISCUSSION OF RESULTS.

Taking the height of the column used in obtaining the results given in the last table as representing the maximum vertical distance through which capillary movement will take place in moist Sea Island soil, we find the limit of capillary action to be 165 cm. in moist soil, as compared with a capillary rise of 36 cm. in air-dry soil. The capillary rise in moist Sea Island soil is therefore about 4.5 times as great as when the soil is in a dry state.

We are thus led to see that the capillary rise in dry soils furnishes no reliable criterion of the extent of capillary movement in the soil, unless we find eventually that for soils in general a definite relation exists between the capillary rise in the air-dried soil and the limit of capillary movement in the moist state.

Furthermore, the rate of capillary movement is of equal or even greater importance than the extent, since it is the *amount* of water furnished at any desired point that constitutes the important criterion. It is therefore important to know the rate at which water can be furnished through capillary action for a soil column of any length up to the limiting value; for, while a soil may be capable of maintaining capillary action through a long column, the rate of translocation of the water may be so small as to be of little practical value.

WORK OF OTHER INVESTIGATORS.

Stewart's investigations.—Recently, at our suggestion, Mr. J. B. Stewart investigated the capillary limit of three Michigan soils, the work being carried on under the direction of Prof. J. A. Jeffery at the Michigan Agricultural College. The soils used were all sandy, as shown by the following mechanical analyses, which represent in each case the average of three determinations:

Soil.	2 to 0.05 mm.	0.05 to 0.01 mm.	>0.01 mm.
	Per cent.	*Per cent.*	*Per cent.*
1	97.6	0.8	0.1
2	96.3	1.2	.3
3	88	7.3	.7

The following table gives the results of Stewart's measurements. The capillary limit of each soil, both in a dry and a moist state, was determined, and duplicate measurements were made in each case.

Capillary limit of three Michigan soils.

Measurement.	Soil 1.		Soil 2.		Soil 3.	
	Dry.	Moist.	Dry.	Moist.	Dry.	Moist.
1	31.2	110	57.5	137.5	85	168.1
2	32.5	115	58.7	146.2	88.7	181.2
Mean	31.8	112.5	58.1	141.8	86.8	174.1

It is evident from the comparison of the mean values given in the above table that no constant ratio exists between the capillary limits of soils in a dry and in a moist condition. Stewart[a] has found, however, a somewhat complicated empirical relation between these three soils. If we let X_m represent the capillary limit of any soil X when moist, X_d the capillary limit of the same soil when dry, and Y_m and Y_d the corresponding values for any other soil Y, then—

$$\frac{X_m - Y_m}{X_d - Y_d} = \text{constant.}$$

Substituting his experimental results in the above formula, Stewart obtained for successive pairs of soils the values 1.13, 1.12, 1.14 for his constant, which shows a very satisfactory agreement. These soils are, however, all sandy, and further experiments with heavier soils are of course necessary to test the general applicability of this relation.

King's investigations.—In a paper which appeared during the progress of this work, King[b] concludes, from his experimental results, that evaporation at the surface of a moist column of soil may cause a capillary adjustment, and consequently a drying of the soil 10 feet below the surface. King's method consisted in filling a galvanized-iron tube, closed at its lower end, with moist soil containing as nearly as possible a uniform amount of water, exposing to surface evaporation for a long period (three hundred and fourteen days in one instance), and then cutting the tube into 6-inch sections and determining the water content of each. From the distribution of water at the beginning and end of the experiment he determines the distance through which an upward capillary movement has taken place.

King's method of procedure appears perfectly valid for all cases in which the final water contents of the lowest sections are less than the initial values. It should be observed, however, that this method does

[a] Thesis, "Capillary rise of water in soils," Mich. Agr. Coll., 1901.

[b] Sixteenth Annual Report Wis. Expt. Sta., 1899, p. 214.

not give the capillary limit of the soil, but shows only that the capillary limit exceeds the length of the soil column used. In case the water content of some of the lower sections is greater at the end than at the beginning of the experiment, no definite conclusions regarding the capillary limit can be reached.

EXPLANATION OF DIFFERENCES IN CAPILLARY ACTION IN DRY AND MOIST SOILS.

It will be of interest to consider briefly the probable cause of the observed differences in the capillary rise of water in soils when dry and when in a moist state. This difference is the result of the difference in the surface conditions of the soil grains in the two cases.

In general, the capillary movement of a liquid over the surfaces of a solid may be looked upon as the resultant of three surface forces, or surface tensions, as they are more commonly known. For convenience we may designate them as the surface tensions of the solid-air surface, solid-liquid surface, and air-liquid surface, respectively. The inherent property of these surface tensions is to reduce the area of their respective surfaces to the greatest possible extent. Thus the solid-air surface force tends to reduce the area of its surface to a minimum by drawing the liquid out over the surface. This is opposed by the surface tensions of the air-liquid and liquid-solid surfaces, since the areas of both these surfaces are in general increased by this process. Further motion of the film ceases when these forces come into equilibrium.

In the case of the air-dry soil we have all of these surface forces taking part in the capillary rise of the water, the solid-air surface producing the motion and the liquid-solid and air-liquid surface forces, together with the weight of the liquid, opposing it. We thus see that the two more important surface forces, namely, those pertaining to the solid-air and air-liquid surfaces, are here opposing each other. In the moist soil, however, we have quite another condition. A film of the liquid covers all the surfaces of the soil grains. Since this film, once established, is maintained in a saturated atmosphere, it follows that the solid-air and solid-liquid surface forces no longer play any part in the capillary movement, which is produced entirely by the air-liquid surface force and is opposed only by the weight of the liquid column.

These considerations would lead us to expect a greater capillary range in the moist soil, which conforms with our experimental results. Furthermore, we have no reason to expect the same capillary rise in dry soils of the same texture and structure on account of differences in surface conditions. In the moist soil this disturbing factor disappears, and identical conditions in structure and texture should give the

same capillary limit, independent of the actual nature of the soil grains.[a]

APPLICATION OF LABORATORY RESULTS TO FIELD CONDITIONS.

Laboratory investigations on the capillary rise of water in dry soils are of relatively little value as applied to field conditions, since it is very seldom that we have occasion in the field to deal with the capillary rise of water in an air-dried soil. Investigations on the limit of capillary movement in moist soils, however, show definitely to what extent the soil is able to raise water through capillary action. Thus if we know the capillary limit of the soil and the depth to which the roots of the crop extend, we can say definitely whether the water table is the source of a portion of the plant's water supply.

Extensive capillary action is a very important property of a soil, even if the capillary limit does not extend to the water table, owing to the fact that a heavy precipitation at the surface causes a wave of saturation, so to speak, to pass downward into the soil. We have here a temporary water table which is slowly moving downward, but which is capable of supplying moisture to the plant so long as it is within the zone of capillary action. Consequently the greater the capillary limit the longer would this transient supply be available.

In this connection, however, it must again be emphasized that it is not so much the great distance through which capillary action will take place that is of economic importance, but rather the rate at which water is supplied from that distance. The capillary limit of a soil increases as the soil particles become smaller, but the resistance offered to the movement of the water soon becomes so great as to overbalance the advantage of the increased capillary range. An extensive capillary action is of little value if it is not able to supply the water necessary for the existence of the plant during a temporary drought.

[a] In this connection certain field observations of Professor King (Annual Report Wisconsin Expt. Sta., 1893, p. 183) are of much interest. He observed, in taking samples of soil just before and again after showers, that the soil at some distance below the surface had become actually drier after the rain. This fact was further verified on two different occasions on field soils by first taking samples of soil at different depths below the surface and then applying a weighed amount of water, and after a time taking samples again. In these trials it was found that the upper layers of soil contained more water than the amount added, while the lower layers were drier. Professor King explains this as follows: When the surface of the soil has reached a certain degree of dryness water ceases to rise rapidly from below. Where, however, water is added in sufficient quantity to moisten the dry soil up to the point at which capillary action is again established, an additional amount of water is brought up from the damp soil below. When such conditions exist, the beneficial results of a light rain are not to be found simply in the comparatively small amount of water that has fallen, but in the much greater capillary supply which has thus been made available to shallow-rooted plants.

SUMMARY.

From the results of the investigation described in this paper the following conclusions may be drawn:

(1) The extent of capillary action in a soil under field conditions is not represented by the capillary rise of water in the air-dried soil.

(2) The extent of capillary action may, however, be found by determining the limiting height through which capillary movement will take place in a moist soil.

(3) If a general relation can be established between the capillary rise of water in dry and in moist soils, then the capillary rise in air-dried soils may be used as a basis for investigating the behavior of the soils under field conditions, and possesses the advantage of greater simplicity. If no definite relation can be found, then the determinations of the capillary rise in dry soils are without value.

(4) It is consequently important that investigators in this line should determine the limit of capillary movement in moist soils in which they are interested, both to obtain reliable data regarding the extent of capillary action and to determine the ratio of capillary action in dry and moist soil.

(5) The true limit of capillary movement may be determined by finding the limiting height of a soil column from the upper surface of which evaporation proceeds at a finite, continuous, and approximately uniform rate, the supply being obtained from a reservoir at the base of the column. The rate of evaporation may be determined directly by weighing the system, or less accurately by measuring the height of the water in the reservoir.

(6) For Sea Island soil we have found the capillary rise in dry soil to be only 37 cm., while the limiting value of capillary movement in a vertical column of moist soil is not less than 165 cm., or 4.5 times as great.

(7) The rate at which water can be supplied at a given point by capillary action through soil columns of various heights is of fundamental importance when the plant is dependent upon capillary movement for its water supply. This determination can readily be made by the methods described.

FILTRATION OF SUSPENDED CLAY FROM SOIL SOLUTIONS.

By Lyman J. Briggs.

INTRODUCTION.

One of the features of the Soil Survey as conducted by the Department of Agriculture in the western part of the United States is the determination of the approximate amount of water-soluble mineral salts present in the soil. The total amount of salts is determined approximately by measuring the electrical resistance of the saturated soil, a method which has been described in earlier publications of the Bureau of Soils. In addition to the total amount of salts, however, it is desirable to know the relative amounts of carbonates, hydrogen carbonates, and chlorides, which are determined volumetrically according to methods described elsewhere by Dr. F. K. Cameron.[a]

NECESSITY FOR REMOVAL OF SUSPENDED CLAY.

The volumetric determinations are made from a solution of the soluble salts of the soil obtained by shaking a measured amount of soil in a given volume of water. Owing to the presence of suspended matter in these solutions the determinations of the end reactions of the titrations by the change in color of the indicator is very difficult except in sandy soils. Clay soils are particularly difficult, owing not only to the large amount of suspended material, but also to the fact that the suspended clay is in many cases very similar in color to one or more of the indicators employed, which are usually phenolphthalein, methyl orange, and potassium bichromate.

A still more serious difficulty lies in the fact that frequently the suspended matter in such solutions consists largely of very small particles of calcium and magnesium carbonate. Consequently, when titrations are made for carbonates and hydrogen carbonates, this undissolved material goes into solution as the portion already in solution reacts with the acid used in titration, and an amount of soluble material greatly in excess of that actually in solution in the soil waters at any one time is thus indicated. Such determinations are

[a] Report 64, U. S. Dept. Agr.; Am. Chem. Jour., 23, 471 (1900); Bul. 18, Bureau of Soils, U. S. Department of Agriculture, 77 (1901).

consequently apt to lead to the impression that the more soluble sodium carbonate is present in harmful amounts, which may or may not be the case.

PREVIOUS METHODS OF REMOVING SUSPENDED MATERIAL.

Two methods have heretofore been used in the field to overcome these difficulties, but neither has proved satisfactory. The first method consists simply in allowing the material to stand until the suspended material has settled to the bottom, when the supernatant liquid is decanted. This method has the disadvantage of requiring relatively long periods of time for the sedimentation to take place, which renders it impracticable for field work. For clay soils this method is, for obvious reasons, not at all suitable.

The second method consists in the flocculation of the suspended material by the addition of a salt. For this purpose a salt must be chosen which is not being estimated and which will not interfere with the titration. The alums are very effective flocculating agents, but do not fulfill the second condition imposed. Sodium sulphate has been the salt employed by Mr. F. D. Gardner for this purpose, since it is not estimated in the volumetric determinations. This salt, while flocculating the clay with considerable rapidity and materially lessening the time required for sedimentation, is still greatly inferior to the alums in this respect and occasions a loss of time.

FILTRATION OF SUSPENDED CLAY.

On account of the difficulties mentioned above, an investigation of the subject was undertaken at the request of the field men with the hope of devising ultimately some satisfactory method of separating the suspended material from the solution and which at the same time should be adapted to field work. The latter condition demanded, first, reasonable quickness in making the separations; second, the assurance that the concentration of the solution is not materially changed during the process of separation, and finally, a light, portable apparatus, substantial in structure and easily manipulated.

Two methods of attacking the problem came to mind, namely, the use of centrifugal force to hasten the rate of sedimentation, and simple filtration. Experience with centrifugal apparatus in the mechanical analysis of soils has shown that the removal of the clay by this means is not feasible under field conditions, since extremely high speeds are necessary to throw down the clay particles, and with hand-driven apparatus this can be obtained only when very small amounts of solution are employed.

In considering methods of filtering, pressure was selected to increase the rate of filtration in place of the partial vacuum usually employed

in laboratories, since by the pressure method any desired difference in pressure on the two sides of the filter can be obtained, while with a vacuum one is of course limited to a maximum difference of pressure of one atmosphere.

CONSTRUCTION AND OPERATION OF FILTER.

The construction of the filter finally adopted is shown in vertical section in fig. 5. The filter consists of an unglazed tube of porcelain, such as is used in the Pasteur-Chamberland water filter. This tube is closed at one end, the other end being cemented in a glazed cap of porcelain, provided with a tubulure, which fits into a rubber gasket, as indicated in the drawing. The filter tube is inclosed in a metal cylinder which serves as the receptacle for the solution to be filtered.

The pump, which is of the compression type, forces air through the check valve into an air chamber, so that a continuous pressure on the liquid can be obtained without constant pumping. The air chamber also serves as a support for the cylinder containing the filter tube.

The muddy solution to be filtered is introduced into the cylinder by unscrewing the latter from the air chamber. About 225 c. c. of the solution can be thus introduced when the filter tube is in position. The cylinder is then once more connected with the air chamber and a few strokes given to the pump, when the clear filtrate begins to issue from the tubulure in an unbroken stream. About three minutes are required to filter 150 c. c. of the solution.

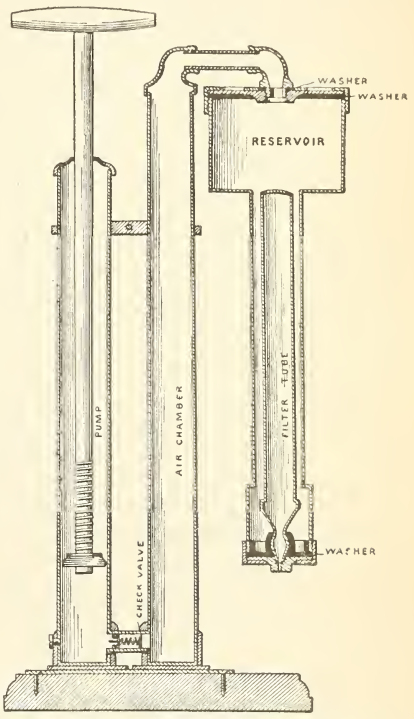

FIG. 5.—Vertical section of filter pump, showing piston, check valve, air chamber, reservoir, and filter tube.

The last portion of the solution filters somewhat more slowly, since the air pressure is reduced by air passing through the uncovered portion of the filter. A peculiar phenomenon is here introduced. The air in being compressed has its temperature raised considerably, and in passing through the filter it becomes saturated with water vapor at a temperature higher than that of the surrounding air. Consequently, as the air issues from the orifice the water vapor in excess of that

saturating the air at atmospheric temperature condenses, forming a cloud about the base of the cylinder.

The filter tube can be easily removed for cleaning by unscrewing the cap at the bottom. A small brush with stiff bristles will be found very useful in washing off the clay which accumulates on the surface.

The check valve will sometimes be found "set," if the pump has not been used for some time. The screw directly opposite the valve should then be removed, and the valve loosened by pressing back the stem with some suitable instrument.

The filter tube when saturated contains about 20 c. c. of water in its interstitial spaces. It is therefore necessary to discard the first 40 or 50 c. c. passing through the filter in order to be sure that the filtrate is not being mixed with the solution previously filtered or diluted with the water used in washing.

EXAMINATION FOR CHANGE IN CONCENTRATION THROUGH FILTRATION.

Solutions of sodium chloride were first examined for change in concentration through filtration. Three concentrations were used—approximately one-tenth, one-hundredth, and one-thousandth normal. The results are given below:

N/10 NaCl:

Before filtering—

25 c. c. NaCl = 23.20 N/10 $AgNO_3$
25 c. c. NaCl = 23.30 N/10 $AgNO_3$

Mean, 23.25 c. c.

After filtering—

25 c. c. NaCl = 23.20 c. c. N/10 $AgNO_3$
25 c. c. NaCl = 23.25 c. c. N/10 $AgNO_3$

Mean, 23.225 c. c.

N/100 NaCl:

Before filtering—

25 c. c. NaCl = 25.00 c. c. N/100 $AgNO_3$
25 c. c. NaCl = 25.00 c. c. N/100 $AgNO_3$

Mean, 25.00

After filtering—

25 c. c. NaCl = 25.15 c. c. N/100 $AgNO_3$
25 c. c. NaCl = 25.00 c. c. N/100 $AgNO_3$

Mean, 25.075

N/1000 NaCl:

Before filtering—

50 c. c. NaCl = 5.5 c. c. N/100 $AgNO_3$
50 c. c. NaCl = 5.6 c. c. N/100 $AgNO_3$

Mean, 5.55 c. c.

After filtering—

50 c. c. NaCl = 5.5 c. c. N/100 $AgNO_3$
50 c. c. NaCl = 5.6 c. c. N/100 $AgNO_3$

Mean, 5.55 c. c.

These results show no evidence of change in concentration through filtration, indicating that for this salt the adsorption is less than the experimental error.

Solutions containing a mixture of sodium carbonate and sodium-hydrogen carbonate were also tested. Before filtering the solution showed the following composition:

	Phenol-phthalein.		Methyl orange.		Total.	
10 c. c. =	1.9 c. c.	+	2.32 c. c.	=	4.22 c. c.	N/10 HCl
10 c. c. =	1.9 c. c.	+	2.35 c. c.	=	4.25 c. c.	N/10 HCl
				Mean,	4.23	

After filtering, discarding the first 40 c. c., the following results were obtained:

	Phenol-phthalein.		Methyl orange.		Total.	
10 c. c. =	1.9 c. c.	+	2.32 c. c.	=	4.22 c. c.	N/10 HCl
10 c. c. =	1.9 c. c.	+	2.28 c. c.	=	4.18 c. c.	N/10 HCl
				Mean,	4.20	

These results show a small change in the concentration of the solution but no disturbance of the equilibrium between the sodium carbonate and sodium hydrogen carbonate.

An approximately N/100 Na_2CO_3 solution was then tested, with the following results:

Before filtering:

	Phenol-phthalein.		Methyl orange.		Total.	
25 c. c. Na_2CO_3 =	12.30 c. c.	+	13.20 c. c.	=	25.50 c. c.	N/100 HCl
25 c. c. Na_2CO_3 =	12.10 c. c.	+	13.20 c. c.	=	25.30 c. c.	N/100 HCl
25 c. c. Na_2CO_3 =	11.80 c. c.	+	13.55 c. c.	=	25.35 c. c.	N/100 HCl
25 c. c. Na_2CO_3 =	12.00 c. c.	+	13.20 c. c.	=	25.20 c. c.	N/100 HCl
Mean,	12.05 c. c.		13.29 c. c.		25.34 c. c.	

After filtering:

	Phenol-phthalein.		Methyl orange.		Total.	
25 c. c. Na_2CO_3 =	11.22 c. c.	+	13.48 c. c.	=	24.70 c. c.	N/100 HCl
25 c. c. Na_2CO_3 =	11.18 c. c.	+	13.62 c. c.	=	24.80 c. c.	N/100 HCl
25 c. c. Na_2CO_3 =	11.00 c. c.	+	13.75 c. c.	=	24.75 c. c.	N/100 HCl
25 c. c. Na_2CO_3 =	11.12 c. c.	+	13.68 c. c.	=	24.80 c. c.	N/100 HCl
Mean,	11.13 c. c.		13.63 c. c.		24.76 c. c.	

These results show a decrease in concentration of $\frac{25.34-24.76}{25.34}$, or about 2 per cent, through the process of filtering. It will also be seen that the amount of bicarbonate in the solution has been slightly increased, due to the carbon dioxide introduced into the solution during the filtration.

An approximately N 1000 Na_2CO_3 solution was next used. The first 40 c. c. passing through the filter were discarded; the next 100 c. c. were saved and titrated.

Before filtering:

	Phenol-phthalein.		Methyl orange.		Total.	
50 c. c. Na_2CO_3 =	0.98	c. c. +	4.42	c. c. =	5.40	c. c. N 100 HCl
50 c. c. Na_2CO_3 =	1.00	c. c. +	4.40	c. c. =	5.40	c. c. N 100 HCl
Mean.	0.99	c. c.	4.41	c. c.	5.40	c. c.

After filtering:

	Phenol-phthalein.		Methyl orange.		Total.	
50 c. c. Na_2CO_3 =	0.18	c. c. +	4.22	c. c. =	4.40	c. c. N 100 HCl
50 c. c. Na_2CO_3 =	0.18	c. c. +	4.50	c. c. =	4.68	c. c. N 100 HCl
Mean.	0.18	c. c.	4.36	c. c.	4.54	c. c.

These results show a serious diminution in the concentration of the solution, amounting under the existing conditions to about 15 per cent. The equilibrium between the carbonates and the bicarbonates has also been seriously disturbed.

If the diminution of the concentration of the solution is due wholly to adsorption, then when a sufficient quantity of salt has been adsorbed by the filter to bring it into equilibrium with the solution the remainder of the solution will pass through the filter unchanged in concentration. But Professor King, in testing the applicability of the filter to the field study of the very dilute soil solutions found in humid climates, has observed for dilute solutions of carbonates, sulphates, nitrates, and phosphates an *increase* in the concentration of the *unfiltered* portion of the solution remaining in contact with the filter tube after a filtration. As Dr. Dorsey has suggested, this would follow from the tube behaving as an imperfect semipermeable membrane, allowing the water to pass through the filter walls more readily than the dissolved salt. We have to deal, therefore, not simply with the adsorption of the salt by filter, but with a change in concentration of the unfiltered portion of the solution as well. This latter fact complicates the problem to a considerable extent. Let us first consider the two limiting cases.

If no convection current exists in the filtered portion of the liquid, the concentration of the solution about the filter will gradually increase until, as a result of the increased concentration, the salt passes through

the filter as rapidly as it is supplied by the unfiltered solution. When this point is reached, if the filter is in equilibrium with the solution so far as adsorption is concerned, the filtrate will have the same concentration as the original solution, and this concentration will not change during the remainder of the filtration.

On the other hand, if the unfiltered portion of the solution is kept thoroughly agitated so as to maintain the same concentration throughout, the concentration of the unfiltered solution will gradually increase, owing to the separation of the solute by the filter. Under these conditions the concentration of the filtrate will increase continuously with the time, and eventually be greater than that of the original solution.

In an actual filtration one is, of course, working somewhere between the limiting cases just mentioned. We have, however, endeavored to choose the conditions so as to attain the limit first described as nearly as possible. That is, to prevent the salt separated at the filter from moving out into the main body of the solution. The annular space about the filter has, accordingly, been made very small, to prevent convection currents as much as possible. The filtration should also be carried on rapidly and the tilting or shaking of the apparatus avoided for the same reason. A true diffusion of the salt separated would take place so slowly as to be negligible in this connection.

The following determinations were made to determine for various salts the variation in concentration of the filtrate as compared with the amount filtered. The filter pump was not used in these determinations, the filter tube being inserted into the bottom of a vertical glass tube of slightly larger diameter, a tight joint being made by large rubber tubing. The tubulure of the filter passed through a rubber stopper, which was in turn inserted in a filtering flask. The volume of the annular space surrounding the filter tube was 37 c. c. The glass tube above the upper end of the filter had a capacity of 500 c. c. This arrangement differed from the filter pump only in having a larger reservoir, and thus avoiding the necessity of introducing an additional amount of solution during the course of an experiment.

N/1000 K_2SO_4.—*Time of entire filtration, 15 minutes.*

Description.	Conductivity $\times 10^3$.	Mean.
Original solution	0.2272 .2315 .2304 .2304	0.2299
First 50 c. c. to pass through filter tube	.1426 .1416 .1406	.1416
Second 50 c. c.	.2191 .2179	.2185
Third 50 c. c.	.2193 .2193	.2193

N/1000 K_2SO_4.—*Time of entire filtration, 15 minutes*—Continued.

Description.	Conductivity $\times 10^3$.	Mean.
Fourth 50 c. c.	0.2230 .2262	0.2246
Fifth 50 c. c.	.2273 .2273	.2273
Sixth 50 c. c.	.2262 .2273 .2273 .2319	.2282
Seventh 50 c. c.	.2296 .2296	.2296
Eighth 50 c. c.	.2306 .2299	.2303
Ninth 50 c. c.	.2299 .2288 .2288 .2299	.2294
Tenth 50 c. c.	.2299 .2306 .2293	.2299
Portion left around filter	.2340 .2325 .2351	.2339

These results for potassium sulphate show a gradual increase in conductivity up to the seventh 50 c. c. passed through the filter. Subsequent portions have practically the same concentration as the original solution. It will be noted that the portion remaining around the filter is about 2 per cent more concentrated than the original solution, confirming Professor King's observations.

N/1000 KCl.—*Time of filtration, 26 minutes.*

Description.	Conductivity x 10^3.	Mean.
Original solution	0.2320 .2301	0.2310
Second 50 c. c. portion of filtrate	.2307 .2307	.2307
Fourth 50 c. c.	.2301 .2301 .2302	.2301
Sixth 50 c. c.	.2288 .2299 .2309 .2302	.2302
Portion remaining around filter	.2306 .2312	.2309
Portion remaining around filter after 500 c. c. of the solution had passed through filter in 9 minutes	.2296 .2306	.2302

These results show that potassium chloride solutions are not changed in concentration to any appreciable extent through filtering, the first

portion passing through the filter having the same concentration as the original solution. The same results were obtained with sodium chloride (see p. 34).

We should accordingly expect no increase in concentration of the dissolved salt about the filter, and none was found. Increasing the rate of filtration produced no change.

N/1000 $NaHCO_3$.—*Time of filtration, 21 minutes.*

Description.	Conductivity $\times 10^3$.	Mean.
Original solution	0.1522 .1519	0.1521
Second 50 c.c. to pass through filter	.1131 .1124	.1128
Fourth 50 c.c	.1439 .1412	.1426
Sixth 50 c.c	.1481 .1481	.1481
Eighth 50 c.c	.1505 .1499	.1502
Tenth 50 c.c	.1496 .1501	.1498
Portion remaining around filter	.1559 .1554	.1557

It will be seen from the above results that a sodium bicarbonate solution undergoes a very appreciable change in concentration through filtration, and that the original concentration is not completely attained even after 500 c.c. have passed through the filter. The results also indicate a considerable adsorption of the salt by the filter, since the gain in concentration of the solution remaining around the tube at the end of the filtration is not sufficient to account for the salt removed from the filtrate.

N/1000 KNO_3.—*Time of filtration, 21 minutes.*

Description.	Conductivity $\times 10^3$.	Mean.
Original solution	0.2096 .2105	0.2100
Second 50 c. c	.2000 .2004	.2002
Fourth 50 c. c	.2033 .2045	.2039
Sixth 50 c.c	.2041 .2053	.2047
Eighth 50 c.c	.2058 .2062	.2060
Tenth 50 c.c	.2105 .2110	.2107
Portion left around filter	.2174 .2174	.2174

Potassium nitrate solutions give results similar to potassium sulphate, although the concentration of the filtrate appears to increase less rapidly.

It is interesting to note that an increase in concentration of the unfiltered portion of the solution immediately about the filter tube was found in every case in which the dissolved substance dissociates with the formation of a complex ion, as SO_4, HCO_3, NO_3; while the effect is not obtained with the potassium chloride and sodium chloride solutions, where we have the simple ions, K, Na, and Cl. This suggests that the complexity of the ions may have something to do with their retardation by the filter. We hope to be able to investigate this point further. There appears also to be considerable variation in the filter tubes, the effect being much more pronounced in some tubes than in others.

For many of the determinations given above I am indebted to Mr. A. G. McCall and Mr. Herbert W. Marean.

NOTE ON THE USE OF "HARDENED" FILTER PAPERS IN SEPARATING SUSPENDED CLAY.

Before adopting the porcelain filter some experiments were made with the hardened filter papers of Schleicher and Schüll, with the hope of avoiding the necessity of cleaning the porcelain tube, since a fresh filter could be inserted when necessary. In this work the filter was not folded, but was clamped near its circumference between the base and sides of a cylindrical filter cup of the same external diameter as the filter. The joint was made water-tight by the use of a rubber ring. The filter paper rested, except at its circumference, on a disk of heavy brass gauze, which effectually supported the filter and allowed the filtrate to pass away freely.

This form of filter is a very rapid one, since practically the whole surface of the filter paper is utilized. The rate of filtration depends, of course, upon the pressure applied to the solution in the filter. To secure a satisfactory rate of filtration of solutions carrying clay in suspension some difference of pressure is always necessary, since a medium capable of retaining suspended clay allows the passage of water by gravitation only with extreme slowness.

Experiments with this filter served to emphasize the fact that the size of the clay particles or aggregates varies greatly with different soils. In some soil solutions the clay could be very satisfactorily separated by this filter. In other cases a slight turbidity of the filtrate was noted, while in certain Western samples a considerable amount of clay passed through the filter, which, of course, prevented its general use.